

CHAPTER 6

HYDRAULIC DESIGN OPTION FOR NEW CULVERTS

6.1	Design Option Description	6-1
6.2	Design Process Overview.....	6-2
6.3	Engineering Data Collection and Site Assessment.....	6-4
6.3.1	Channel Topography.....	6-4
6.3.2	Allowable Headwater.....	6-4
6.3.3	Acceptable Outlet Velocity.....	6-4
6.4	Fish Passage Criteria	6-5
6.4.1	Species and Lifestyle	6-5
6.4.2	Hydrologic and Hydraulic Criteria	6-5
6.4.3	Additional Culvert Criteria	6-8
6.5	Hydrologic Analysis.....	6-8
6.6	Hydraulic Analyses	6-9

LIST OF FIGURES

Figure 6-1. Outlet view of a culvert replacement project developed through the hydraulic design option.	6-2
Figure 6-2. Flow chart of the hydraulic design process for new and replacement culverts.	6-3

LIST OF TABLES

Table 6-1. High design flow for fish passage.	6-6
Table 6-2. Low design flow for fish passage.	6-6
Table 6-3. Maximum average water velocity for various culvert lengths.	6-7
Table 6-4. Minimum depth of flow.....	6-7
Table 6-5. Maximum drop at culvert outlet.	6-7

6 HYDRAULIC DESIGN OPTION FOR NEW CULVERTS

6.1 Design Option Description

The hydraulic design option for new fish passage culverts is the option most similar to the conventional method of designing culverts for highway cross drainage. However, a significant difference between these two methods can be seen in the design parameter that plays the key role in determining the culvert configuration. In the conventional approach to hydraulic culvert design, the design parameter that most frequently determines the culvert size is the allowable headwater elevation. In contrast, the fish passage approach to hydraulic culvert design will most frequently size the culvert using a design parameter specifying the maximum velocity within the culvert barrel.

Adaptation of the conventional culvert hydraulic design method to fish passage applications has led to the development of “fish passage criteria” that must be satisfied by the design. In California, there are five distinct classifications of fish species and life stage groupings that have unique fish passage criteria. Use of the hydraulic design option for culvert design requires that the fish species and life stage classification, commonly referred to as the “target population”, be identified so that the appropriate fish passage criteria can be applied. If the target population is not certain, the designer should contact the Biologist or Planner assigned to the project for more information, or another design option should be used.

At present, fish passage criteria regarding acceptable culvert velocity or minimum water depth have not been established for non-salmonid species or non-native species. Because of the lack of criteria, it is not possible to use the hydraulic design option for fish passage culverts needing to pass native non-salmonid fishes or non-native species, unless data can be provided regarding the swimming and leaping performance of the target population. Assuming the lack of such data, the hydraulic design option can be used only for those projects where salmonids are the only species requiring fish passage.

This chapter addresses the hydraulic design option specifically for cases that involve installation of new culverts or the total replacement of existing culverts. Cases that strive to address fish passage deficiencies without removing an existing culvert typically will require additional hydraulic analyses not presented in this chapter. The hydraulic design option for culvert retrofit projects is presented in Chapter 7.

Common language for highway cross drainage design refers to the “culvert design”, but in actuality the design process addresses a broader system of components which must operate in coordination and simultaneously. Consideration of the various elements of a culvert system is useful to a discussion about the various design parameters and criteria associated with the hydraulic design option. The culvert system elements addressed during a hydraulic design typically include the following:

- Upstream channel characteristics – Topographic features influence the horizontal and vertical orientation of the culvert, and flow characteristics and associated water elevations determine compliance with the design criterion relating to allowable headwater elevation.
- Culvert entrance – The culvert entrance invert elevation and the selected end treatment influence the system hydraulic capacity and the response to sediment and debris loadings.
- Culvert barrel(s) – During the preliminary stage of fish passage design, it is common to establish the size and shape of the culvert barrel primarily on the basis of hydraulic criteria

regarding velocity limitations and minimum depth. The conduit material selection commonly depends on structural loading requirements, compatibility with durability factors, and economics.

- Culvert outlet and associated tailwater characteristics – The culvert outlet invert elevation and tailwater levels have a direct influence on the hydraulic operation of the culvert.
- Downstream channel characteristics - The shape, orientation, and material composition of the channel downstream of the culvert influence the tolerance of culvert outlet velocities during high discharge events and operating water depths inside the culvert.

Figure 6-1 shows an example of an installed 72 inch diameter fish passage culvert that was designed using the hydraulic design option. The culvert is located on a tributary of Bertrand Creek in Whatcom County, Washington. The view in the photograph shows the culvert outlet and the tailwater pool developed by placing grade control structures in the downstream channel.



Figure 6-1. Outlet view of a culvert replacement project developed through the hydraulic design option.

6.2 Design Process Overview

The design process for the hydraulic design option consists of several basic elements, as shown in the following flow chart (Figure 6-2). The broader design components as shown in the flow chart are discussed in the following sections of this chapter. A design example is provided in Section 6.8.

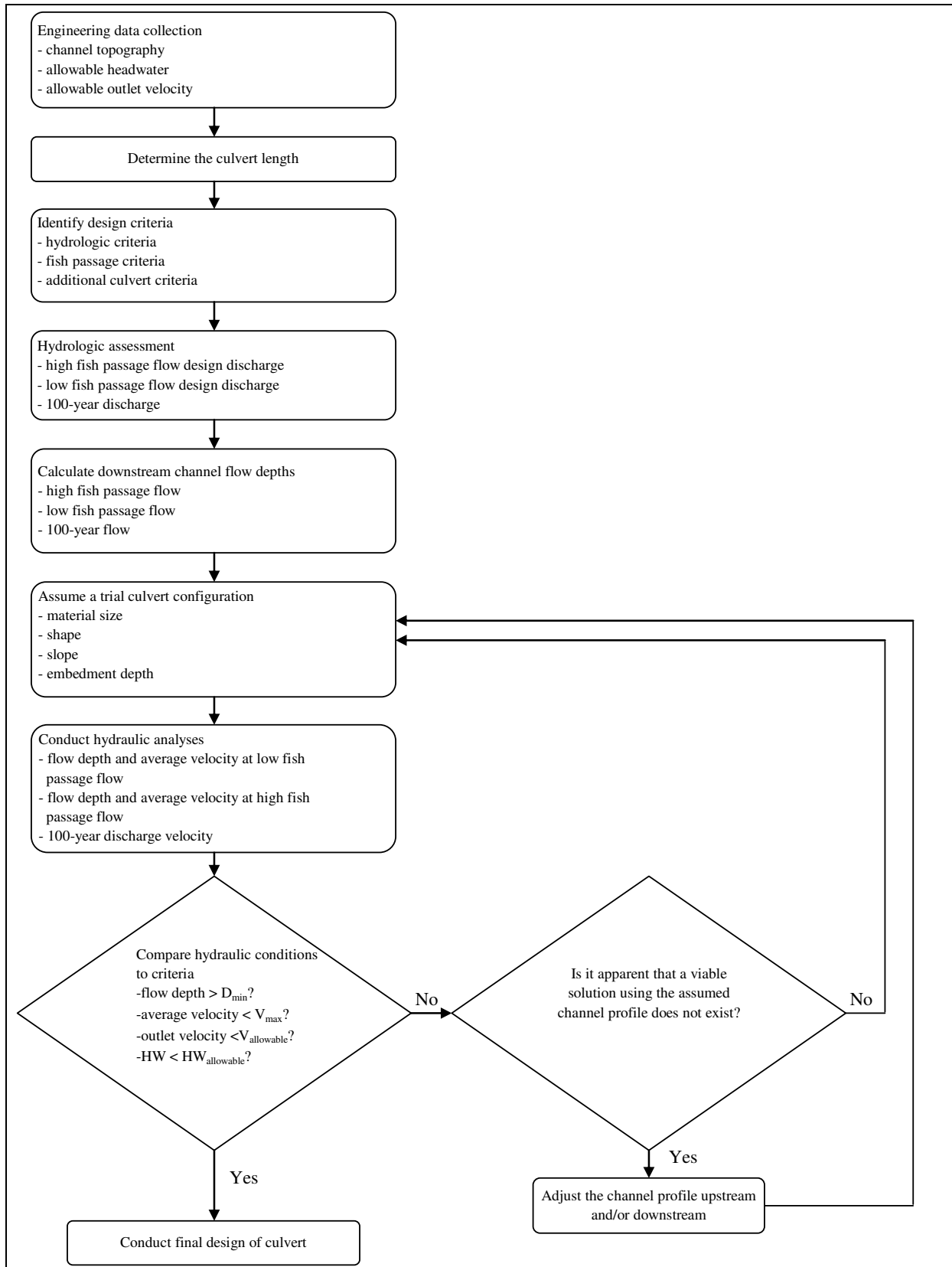


Figure 6-2. Flow chart of the hydraulic design process for new and replacement culverts.

6.3 Engineering Data Collection and Site Assessment

The following activities should be completed early in the hydraulic design process. These activities identify critical site conditions that are likely influence the design requirements necessary to achieve compliance with fish passage and culvert design criteria. In general, the accuracy and level of detail of these initial assessments have a strong influence on the accuracy of any preliminary design plans and their associated estimates of construction cost.

6.3.1 Channel Topography

A topographical survey should be completed to allow determination of the slope and width of the natural channel in the vicinity of the culvert site. The survey boundary and cross-section requirements will be dependent on the extent of significant changes in stream channel slope or width in the vicinity of the culvert. For culvert replacement projects where the channel has been affected by the existing culvert, it may be necessary to extend the survey upstream or downstream to areas unaffected by the culvert so that the natural channel slope and elevation at the culvert site can be interpolated.

6.3.2 Allowable Headwater

Headwater conditions that occur upstream of a culvert installation are a result of the fact that the culvert usually represents a severe constriction in the stream. The headwater is the potential energy necessary to overcome this constriction and associated effects.

In the conventional approach to hydraulic design of a culvert, the allowable headwater is the level to which the culvert headwater may rise before causing an unwanted inundation or damage under the circumstances of a selected design flood. The allowable headwater criterion must be established in reference to the site physical characteristics, such as fill height or elevation level of property or features which would be damaged if inundated. In the conventional approach, this allowable headwater criterion commonly is the limiting factor that establishes the required culvert size.

In contrast, the allowable headwater criteria for fish passage culverts in California is expressed in terms of maximum headwater depths for the 10-year and 100-year peak flood (see Section 6.5). These same criteria are applicable to all fish passage culverts, regardless of the method used for culvert design. A common effect of these explicit headwater limitations is a reduction in the velocities occurring in fish passage culverts, as compared to the velocities in conventional cross drainage culverts under the same design flow conditions.

6.3.3 Acceptable Outlet Velocity

Because a culvert represents a very significant constriction to flow from an unconfined stream, the velocity of flow at the outlet end is often higher than the natural stream velocity. High velocities are most troublesome just downstream from the culvert outlet. Such high velocities represent high energy content in the discharge and can be potentially erosive. This high energy content is often dissipated by turbulence which removes material, undercuts foundations, erodes banks, and damages the culvert, channel, highway embankment, and property adjacent to or near the culvert outfall unless protection is provided,

Analysis of the natural channel velocity will provide estimates of the natural or equilibrium velocity for the stream. Engineering data collection at the site should include documentation of features such as existing slope angles, bank soil types, and rock size, to allow calibration of flow

rate and velocity estimates. Because of the numerous variables involved, it is not reasonable to establish a universal "maximum outlet velocity". It is recommended that a limiting value for acceptable outlet velocity be defined that relates to site-specific conditions.

Basic configuration of the culvert through the design process is evaluated primarily with regard to the allowable barrel velocities and water depths. However, excessive outlet velocity characteristics may require additional treatments or adjustments to the culvert.

6.4 Fish Passage Criteria

6.4.1 Species and Lifestyle

Fish passage criteria established for the hydraulic design option set limits on the hydraulic conditions within the culvert in order to accommodate the swimming ability of target species and sizes of fish. In California, there are five distinct classifications of fish species and life stage groupings that have unique fish passage criteria, reflecting the differences in swimming capabilities of these groupings. The five classifications are:

- Adult Anadromous Salmonids
- Adult Non-Anadromous Salmonids
- Juvenile Salmonids
- Native Non-Salmonids
- Non-Native Species

Information regarding which of the classifications is present at a site should be obtained from the Biologist or Planner assigned to the project. In cases where more than one classification is present, the classification having the weakest swimming ability should be used (i.e. the more stringent fish passage criteria should be used). It is worth noting that, in the process of developing criteria for each of the classifications, the swimming capabilities of the weakest individuals within that classification were used to establish the limits.

At present, there is little data regarding the swimming capabilities of non-salmonid species or non-native species. As a result, the fisheries agencies have not yet established criteria for these two classifications regarding acceptable culvert velocity or minimum water depth. Because of the lack of criteria, it is not possible to use the hydraulic design option for fish passage culverts needing to pass native non-salmonid fishes or non-native species, unless data can be provided regarding the swimming and leaping performance of the target population. In the absence of such data, fish passage culverts for non-salmonid species or non-native species should use an alternative design option.

6.4.2 Hydrologic and Hydraulic Criteria

In addition to accommodating the swimming capabilities of the target population, the fish passage criteria also take into account migration timing and the risk of passage delay for each of the target population classifications. This is accomplished by establishing criteria to define the high design flow and low design flow for fish passage. As an example, adult salmon spawning migrations are commonly timed with freshets having very high flows, whereas juvenile salmon under these same flow conditions are unlikely to be migrating; hence the high design flow for adult salmonids is greater than the high design flow for juveniles.

The high design flow for fish passage is used to determine the maximum allowable water

velocity within the culvert for the referenced event. Where exceedance flow data is available or can be synthesized, use the values for Percent Annual Exceedance Flow shown in Table 6-1 to determine the criterion for the high fish passage flow. If exceedance flow data is not available, the values shown for Percentage of 2-year Recurrence Interval Flow may be used as an alternative.

NOTE: Tables 6.1 through 6.5 are taken directly from the CDFG Culvert Criteria for Fish Passage document (See AppendixB).

Table 6-1. High design flow for fish passage.

Species/Life Stage	Percent Annual Exceedance Flow	Percentage of 2-year Recurrence Interval Flow
Adult Anadromous Salmonids	1%	50%
Adult Non-Anadromous Salmonids	5%	30%
Juvenile Salmonids	10%	10%
Native Non-Salmonids	5%	30%
Non-Native Species	10%	10%

Where flow duration data is available or can be synthesized, use the values for Percent Annual Exceedance Flow shown in Table 6-2 to determine the criterion for the low fish passage flow. If the Percent Annual Exceedance Flow is determined to be less than the Alternate Minimum Flow, use the Alternate Minimum Flow. If exceedance flow data is not available, the values shown for Alternate Minimum Flow may be used.

Table 6-2. Low design flow for fish passage.

Species/Life Stage	Percent Annual Exceedance Flow	Alternate Minimum Flow
		(ft ³ /s)
Adult Anadromous Salmonids	50%	3
Adult Non-Anadromous Salmonids	90%	2
Juvenile Salmonids	95%	1
Native Non-Salmonids	90%	1
Non-Native Species	90%	1

The maximum water velocity within a fish passage culvert for both the high and low fish passage flows shall not exceed the values shown in Table 6-3.

Table 6-3. Maximum average water velocity for various culvert lengths.

Species/Life Stage	Maximum Average Water Velocity (ft/s)				
	Culvert Length (ft)				
	<60	60 -100	100 -200	200 -300	>300
Adult Anadromous Salmonids	6	5	4	3	2
Adult Non-Anadromous Salmonids	4	4	3	2	2
Juvenile Salmonids	1	1	1	1	1
Native Non-Salmonids	Species specific swimming, performance data is required for the use of the hydraulic design option for non-salmonids. Hydraulic design is not allowed for these species without this data.				
Non-Native Species					

The minimum depth of flow within a fish passage culvert for both the high and low fish passage flows shall not exceed the values shown in Table 6-4.

Table 6-4. Minimum depth of flow.

Species/Life Stage	Minimum Flow Depth
	(ft)
Adult Anadromous Salmonids	1.00
Adult Non-Anadromous Salmonids	0.67
Juvenile Salmonids	0.50
Native Non-Salmonids	Species specific swimming, performance data is required for the use of the hydraulic design option for non-salmonids. Hydraulic design is not allowed for these species without this data.
Non-Native Species	

Hydraulic drops between the water surfaces associated with the culvert, the adjacent channel, and any grade control structures should be avoided whenever possible. Where a hydraulic drop is unavoidable, its magnitude should be evaluated for both high and low fish passage flows and shall not exceed the values shown in Table 6-5. If a hydraulic drop occurs at the culvert outlet, a jump pool of at least 0.6 m (2 feet) in depth shall be provided.

Table 6-5. Maximum drop at culvert outlet.

Species/Life Stage	Maximum Drop
	(ft)
Adult Anadromous Salmonids	1.0
Adult Non-Anadromous Salmonids	1.0
Juvenile Salmonids	0.5
Native Non-Salmonids	Where fish passage is required for native non-salmonids, no hydraulic drop shall be allowed at the culvert outlet unless data is presented which will establish the leaping ability and leaping behavior of the target species of fish.
Non-Native Species	

Additional criteria are specified by the fisheries agencies regarding hydraulic conditions exhibited during the 100-year peak flood flow:

- Headwater Depth - The upstream water surface depth above the top of the culvert inlet for the 100-year peak flood shall not be greater than 50 percent of the culvert rise

6.4.3 Additional Culvert Criteria

The following criteria are additional items that may affect the design. It is worthwhile to identify all features of a proposed culvert on any preliminary drawings submitted to fisheries agencies for review, even if the design of those ancillary features is not likely to occur until the final design stage. This approach is also beneficial in developing accurate cost estimates for the project.

- Spawning Areas - The hydraulic design method shall not be used for new or replacement culverts in anadromous salmonid spawning areas.
- Culvert Width - The minimum culvert width shall be 0.9 m (3 feet).
- Culvert Slope - The culvert slope shall not exceed the slope of the stream through the reach in which the crossing is being placed. If embedment of the culvert is not possible, the maximum slope shall not exceed 0.5 percent.
- Embedment - Where physically possible, the bottom of the culvert shall be buried into the streambed a minimum of 20 percent of the height of the culvert below the elevation of the tailwater control point downstream of the culvert. The minimum embedment should be at least 0.3 m (1 foot).
- Multiple Culverts - Multiple culverts are discouraged where the design criteria can be met with a single culvert. If multiple culverts are necessary, a multi-barreled box culvert is preferred over multiple individual culverts.
- Inlet Transitions - A smooth hydraulic transition should be made between the upstream channel and the culvert inlet to facilitate passage of flood borne debris.
- Interior Illumination - Natural or artificial supplemental lighting shall be provided in new and replacement culverts that are over 46 m (150 feet) in length. Where supplemental lighting is required, the spacing between light sources shall not exceed 23 m (75 feet).

6.5 Hydrologic Analysis

A hydrologic analysis is required for culvert design to derive the design discharge or “hydraulic load” of the proposed facility. There are many hydrologic methods in use. However, none are considered to be exact and all are estimating procedures only. Three methods commonly used for estimating streamflow rates for highway and culvert design purposes are:

- Regional flood estimation equations for various recurrence intervals
- The rational method
- Estimates using local stream gaging data.

Reference to a storm event or flow condition usually is made in terms of some statistical probability of occurrence. As an example, reference may be made to a 50-year flood frequency. Such a reference refers to the flood flow which occurs on average once every 50 years. The statistical probability that the 50-year flood will occur in any given year is the reciprocal of 50, or 2% (i.e., $50 = 1 / 0.02$).

The flows that are used for the fish passage design are defined by policy and promulgated through the fish passage criteria described in Section 6.5. The fish passage criteria define the high and low fish passage flows in terms of an exceedance flow. Alternative criteria expressed as a percentage of the 2-year flood flow or an absolute value are provided for cases where exceedance flow data are not available.

The best way to determine streamflow values for design is to use average daily flow records from a USGS streamflow gage on the stream where the culvert is being designed. A more complete discussion of this process is provided in Section 3.4 and Appendix E.

Often there are no streamflow gage records for the stream where the culvert will be installed. When this occurs, it is possible to use regional flood estimation equations, such as those developed by the USGS for regions throughout California and presented as Figure 819.2C of the Highway Design Manual. A further discussion of the use and limitations of this method are presented in Section 3.4.

6.6 Hydraulic Analyses

Use of the hydraulic design option requires that hydraulic analyses be completed to assess flow velocities and water depths in the culvert and the adjacent channel, and to determine the headwater elevation at the culvert entrance. Several types of hydraulic design methods are acceptable for these determinations, varying in their complexity and level of accuracy. Section 3.5 provides a review of the basic hydraulic concepts that are encountered with culvert operations, and it discusses the more common design methods and computer programs that are used in the culvert design process.

Regardless of the specific method selected for hydraulic analysis, the general approach for culvert design is an iterative process. An initial culvert configuration is made with respect to the culvert material, shape, size, and entrance type. Then:

- hydraulic analysis is made for velocity, depth, and headwater elevation
- the results of the analysis are compared to the design criteria,
- if adjustments are necessary, analyze adjusted configurations until an acceptable design is found.

Often, if there is an adjustment to be considered, it will be in the assumed size and/or barrel configuration. In some cases, consideration toward changing the upstream or downstream channel profile may be necessary. Structures for that purpose are described in Chapter 8.